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Informal Report

White Paper on Proton-Nucleus Collisions

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White Paper on Proton-Nucleus Collisions

1) Introduction and Recommendations

The role of proton-nucleus (p-A) collisions in the study of strong interactions has a long history [1]. It has been an important testing ground for QCD [2, 3]. At RHIC p-A studies have been recognized since the beginning as important elements of the program. These include so-called baseline measurements in cold nuclear matter, essential (along with p-p studies) to a systematic study of QCD at high temperatures and densities in the search for the quark gluon plasma. Also accessible is a study of QCD in the small x (parton saturation) regime, complementary to physics accessible in high-energy e-p and e-A collisions [4].

The role of p-A physics at RHIC was reviewed and brought into sharp focus at a workshop conducted in October 2000 at BNL; the agenda is shown in Appendix 1. This document summarizes the case for p-A at RHIC during the period covered by the next Nuclear Physics Long Range Plan. In subsequent sections we cover the Physics Issues, Experiment Run Plans and Schedule, Detector Upgrade Issues, and Machine Issues & Upgrades.

We conclude this section with a list of the principal recommendations for the RHIC p-A program:

- The highest priority is to implement a run plan for RHIC that includes significant p-A and/or d-A running starting in the third run (FY2003) and continuing during the next several running periods thereafter. This requires that some machine development time in FY2002 be devoted to commissioning p-A and/or d-A collisions in RHIC. Plans for FY2003 and beyond should be based on integrated luminosity per nucleon in proton-nucleus comparable to that obtained in proton-proton and nucleus-nucleus running conditions.
- Second priority is to develop and implement detector upgrades over the next 3-5 years that allow a more complete study at RHIC on the physics of cold nuclear matter at small x. This includes forward detectors for tagging, diffraction measurements and Drell-Yan measurements at very small x. Modest R&D funding to anticipate these detector upgrades should be planned starting in FY2002.
- As indicated in Section 7 below, the p-A program can benefit from machine improvements including asymmetric running, higher luminosity and higher energy. Therefore the third priority is to develop the machine capabilities to provide these running conditions. This includes interaction triggers and luminosity measurement

(and monitoring) that can cope with asymmetric IR geometries. Some of these machine developments will require upgrades to the accelerator (e.g., electron cooling of the ion beam) that may be realized only in the 5-year period after the next one.

2) Significance of p-A Physics and Scientific Questions to be Addressed

The advent of the Relativistic Heavy Ion Collider (RHIC), the primary goal of which is to investigate matter at extraordinary temperature and energy density via nucleus-nucleus collisions, will also offer a unique opportunity to study some fundamental questions in strong interactions via p-A collisions. It is important to point out that RHIC, for the first time, will allow us to study p-A interaction in a collider mode. At RHIC, the center-of-mass energy reached in p-A collisions is roughly an order of magnitude higher than any existing fixed-target experiments. Moreover, the large-acceptance collider detectors are capable of measuring many particles produced in the p-A collisions simultaneously, which could provide qualitatively new information not accessible in previous fixed-target experiments.

It has long been recognized that p-A collisions serve an important role in the search for quark-gluon plasma (QGP) in relativistic heavy-ion collisions. Since QGP is in general not expected to be produced in p-A collisions, a comparison of the A-A with p-A data at identical kinematic conditions is crucial for identifying signatures for QGP formation. This was clearly demonstrated in the AGS and SPS heavy-ion programs, which relied heavily on the p-A measurements for interpreting the A-A results. This important role of p-A collisions is clearly valid at RHIC too.

In addition to their connection to A-A physics, the p-A measurements are important in their own right. Many outstanding questions in hadron physics can be well addressed with an active p-A program at RHIC. These questions include:

- What are the valence and sea quark and gluon contents in nuclei? How are they different from those in a free nucleon?
- How do high-energy partons propagate through nuclei? Can nuclei be used as a tool to study space-time evolution of QCD processes?
- Do parton densities saturate at small x? Can they be described by the conventional DGLAP evolution equations at the small-x region?
- What are the sub-structures of Pomeron and mesons? What are the roles of mesons in describing the partonic structures of nucleon and nuclei?

In this document, we will discuss how these questions can be addressed at RHIC and other accelerators with p-A collisions.

3) Achievement Since Last Long-range Plan

Several fixed-target p-A experiments have been successfully completed at Fermilab, CERN-SPS, and AGS. Some highlights from these experiments together with progress in related theoretical work are:

- A series of p-A dimuon production experiments have been carried out at Fermilab in the last decade using 800 GeV proton beams [3]. From the measurement of Drell-Yan cross section ratios of $(p+d)/(p+p)$, Fermilab E866 experiment clearly established the flavor asymmetry of the up and down quarks of the nucleon sea [5] (see Fig. 1). This result strongly suggests that the meson degrees of freedom are important for understanding the parton structure of nucleons. Several theoretical models including meson-cloud, chiral-quark, chiral-quark-soliton, and instanton models have been proposed to explain this asymmetry [6]. These models have distinct predictions for the spin and flavor structure of nucleons, which could be tested in experiments in the near future.

- Recent theoretical work on the propagation of high energy partons through cold and hot nuclear matter predicted a number of surprising effects [7]. First, the total amount of radiative energy loss (through gluon emission) of a parton is predicted to be proportional to L^2, where L is the path length traversed by the parton inside the nuclear matter. This result is contrary to the conventional wisdom that energy loss depends linearly on L. Second, the partonic energy loss in a hot QCD plasma is predicted to be much larger than in a cold matter, suggesting the use of jet-quenching as a signature for QGP formation [8]. The nuclear dependence of Drell-Yan cross sections in 800 GeV p-A collisions was recently analysed to extract information on partonic energy loss in cold nuclear matter [2]. These Drell-Yan data also showed clear evidence for nuclear shadowing of the sea-quark distributions at low x ($x \sim 0.01$).

- Pronounced nuclear effects of charmonium J/Ψ and Ψ' production as a function of longitudinal momentum x_F and transverse momentum p_T were observed in 800 GeV p-A interactions [9] (see Fig. 2). The polarization of J/Ψ and Υ resonances has also been measured recently [10]. The $\Upsilon(2S+3S)$ states were observed to possess large polarization, in striking contrast with the $\Upsilon(1S)$ state.

- Fermilab E791 very recently reported the first measurement of pion's light-cone wave functions by detecting di-jets produced in a diffractive dissociation process [11]. The nuclear dependence of this process has been interpreted as evidence for color-transparency [12]. This study could readily be extended at RHIC to measure the proton's light-cone wave functions via the detection of three jets.

- Several p-A experiments have been carried out at the CERN SPS. The CERES/NA45 and TAPS collaborations have measured low-mass electron pairs in p-Be and p-Au collisions at 450 GeV/c [13]. NA50 measured muon pairs produced in p-Al, p-Cu, p-Ag, and p-W collisions at 450 GeV/c [14]. WA97 measured strange particles production in p-Pb collision at 158 GeV/c [15]. These p-A measurements were crucial for identifying abnormal behavior in A-A collisions such as J/Ψ-suppression, enhancement of strange particle production, and the excess of low-mass lepton pairs.

- Several dedicated p-A experiments have been completed recently at the AGS. In particular, the E910 experiment showed that the centrality and the number of collisions in p-A interaction could be well characterized by the total number of "gray" tracks emitted in a given event [16]. Many observables were found to correlate strongly with the multiplicity of the "gray" tracks. The detection of "gray" tracks is feasible at RHIC, and should be very useful for understanding the p-A and A-A results.

4) Opportunities and Plans for the Future

In the near future, p-A physics can be pursued at two recently commissioned accelerators – RHIC and the Fermilab 120 GeV Main-Injector (FMI). In the longer-term future, the CERN LHC and the 50-GeV Japan Hadron Facility (JHF) will provide additional venues for p-A physics.

The p-A physics opportunities at RHIC include:

1. Probing the parton distributions in nuclei at small x

    - Di-leptons from the Drell-Yan process are sensitive to antiquark distributions in nuclei. For 100 GeV (250 GeV) protons colliding with 100 GeV·A nuclear beams at RHIC, one will be able to reach values of x down to 1×10^{-3} (5×10^{-4}). This will extend the current reach in low x by roughly two orders of magnitude. Figure 3 shows the kinematic coverage in x and the expected statistical accuracy for a two-month run at PHENIX. Qualitatively new information on the sea-quark content in nuclei, such as shadowing and non-linear saturation effects, could be revealed. In principle, saturation effects for high-density partons at small x could also be searched for in the p-p or e-p collisions. However, by using a heavy nucleus in e-A or p-A collisions, the onset of the saturation effects can occur at a much larger value of x due to the $A^{1/3}$ enhancement factor for the partonic density. The flavor asymmetry of sea-quark distributions in the nucleon could also be explored to very low x.
    - The nuclear dependence of the gluon distribution is practically unknown. At RHIC, the gluon content of the nucleus at a wide range of x could be measured using a variety of hard processes [17], including direct-γ production, γ-jet production, di-jet production, heavy-quark production, high-p_T single-muon production, and low-mass high-p_T dimuon production [18]. Indeed, any

hard processes suitable for extracting gluon polarization information in the RHIC-spin program would also be ideal for probing the nuclear gluon distributions in p-A collisions. These results will provide new information on the gluon content of nuclei, which is closely connected to one of the physics goals of a possible future e-A collider.

- Parton distributions in nuclei provide essential input for predicting interesting observables in heavy-ion collisions. In particular, cross sections for mini-jet production and for other hard processes depend sensitively on how the parton distributions are modified in nuclei (as compared to those in nucleons) [19]. Therefore, the study of quark and gluon shadowing in nuclei is crucial for interpreting A-A collision results. [20].

2. Hard diffractive processes

- The collider kinematics coupled with large-acceptance detectors at RHIC is ideal for studying semi-inclusive process where particles emitted in coincidence with a hard process are detected. One example is the hard diffractive process that was studied extensively at the HERA e-p collider [21] and at $\bar{p}-p$ colliders [22]. By detecting forward-going energetic neutrons or protons in coincidence with a hard process such as deep-inelastic scattering or di-jet production, information on the partonic structures of Pomerons and/or mesons were obtained at HERA [23]. At RHIC, hard diffractive processes can be studied for the p-A system for the first time. Unique information such as the nuclear dependence of the hard-diffractive process could be obtained. The interesting relation [21] between diffractive processes and small-x physics could be further explored. Moreover, the polarized beam at RHIC offers a unique opportunity to study spin-dependence of the diffractive process.
- The recent measurement [11] of the light-cone wave function in pions using the diffractive dissociation method can be readily extended at RHIC by scattering proton beam off nuclei. The signals will involve two or three jets emitted along the proton beam direction carrying most of proton's momentum [24]. The Fock space q^3 as well as the q^2q components of the proton can be determined. The role of color transparency in the production of coherent forward jets can be further studied.

3. Polarized protons

- P-A physics with polarized protons and possibly also with polarized light nuclei such as d, ^{3}H, ^{3}He and ^{19}F provides an additional approach [25]. For example, these measurements can study spin dependence in the EMC effect. $\vec{p}+\vec{n}$ interaction can be measured with $\vec{p}$ colliding with polarized ^{3}He or deuteron beams. RHIC's spin and p-A capabilities together result in a unique high-energy facility.

The 120 GeV FMI and the planned 50 GeV JHF are ideal for studying parton distributions in nucleons or nuclei at large x ($x > 0.2$) (see Fig. 4) and are very much complementary to the p-A program at RHIC. Experience from the RHIC p-A program will also be very valuable for planning p-A experiments at LHC.

5) Experiment Run Plans and Schedule

All the RHIC experiments have long-standing plans to perform comparison runs with existing detectors as part of the systematic study of hot and dense nuclear matter. Examples of comparison measurements and of fundamental QCD measurements have been listed in the previous section.

Some general features of a comprehensive p-A program can be inferred from the plans of the four RHIC experiments as presented [27] at the Workshop:

- p-A running ought to be available in FY2003. Machine studies, discussed in the next section, need to be planned in time for the demands of the p-A program, i.e., not later than the 2002 RHIC run.
- Sufficient statistics for comparison p-A running may require calendar time on the same order as p-p and A-A running. Depending on the merits of the physics case for fundamental QCD measurements outlined in this report, one could foresee future RHIC runs that are largely dedicated to p-A.
- The ability to run p-A with protons in either the blue or the yellow ring is still important. The current RHIC experiments all have interests and capabilities here but all have "upstream-downstream" asymmetries to a greater or lesser extent.

6) Detector Upgrades

Some physics topics available with p-A collisions benefit from upgrades to the present RHIC detectors. The most commonly identified upgrade is forward tagging. These would comprise "Roman Pot" detectors in the outgoing beam directions. They can be used to detect forward-going baryons to select specific proton-meson processes. This is straightforward and not very expensive technology, already being employed at RHIC in the p-p total cross-section measurement [28]. The forward-tagging of the nucleus would be a much more challenging task. Some preliminary design consideration has been presented in the context of the e-A collider [29].

More extensive upgrades aimed at p-A physics involve new or enhanced detector systems. For example, measurement of Drell-Yan production in PHENIX as presently configured is limited to $x_2 \geq 10^{-3}$ by the acceptance of the muon spectrometers. To extend the x_2 coverage to the kinematic limit, a small very forward angle di-muon spectrometer was suggested [30] at the Workshop. In another example, both STAR and PHENIX considered [31] high precision vertex trackers for open charm measurements. These are presumably the same vertex tracking detectors that those experiments are considering for enhanced charm measurements in the A-A program. Both the forward muon spectrometer and the precision vertex detectors are major projects, comparable in cost and timescale to the detectors funded under the RHIC AEE program (i.e., of order $5M - $10M and 5 years).

Although there is currently no new additional experiment proposed, it is foreseeable that a dedicated p-A experiment in the future with an emphasis on forward/backward detector coverage for exclusive channels may provide unique physics opportunities beyond the existing RHIC experiments.

7) Machine Issues and Upgrades

The pA Workshop brought to the fore a number of areas of accelerator development that are particular to p-A physics [32]:

- IR geometry - at equal energies per nucleon proton and heavy ion beams have different magnetic rigidities. Head-on p-A collisions require the beams to be angled by several milliradians relative to the trajectory for equal species. This requires the DX magnets to be moved and has negative implications for the acceptance of the present zero-degree calorimeters in RHIC.
- Asymmetric running - at equal magnetic rigidity, proton and gold beams have about 250 and 100 GeV/nucleon respectively. This has advantages for extending measurements to higher $\sqrt{s}$ and lower x. It also leaves the DX magnet position and ZDC acceptance untouched. However, there are questions yet to be resolved about how to fit these two orbits of different energy into the RHIC aperture.
- Many of the proposed measurements could benefit from an increase of the beam luminosity by a factor of 3-5.
- d-A instead of p-A - deuterons are much closer in Z/A to heavy ions than are protons, so some of the above issues are moot with deuterons. They would also provide separate p-A and n-A information with appropriate tagging of the spectators. Deuterons would also provide comparison running (i.e., at 100×100 GeV/A) with nearly the same IR geometry as p-p and A-A. However the acceleration of deuterons in RHIC requires work on the ion source and the new RFQ. The pros and cons for the three possible running modes are shown in Fig. 5.

It seems likely that both asymmetric p-A running and d-A running at 100 GeV/A will be highly desirable and preferable to p-A at 100 GeV/A for many applications. The issues enumerated above in this section require machine studies and some R&D. As mentioned in the previous section, the experiments would like to begin accumulating nucleon-nucleus data by 2003 at the latest, so these studies and R&D efforts should be incorporated into RHIC planning very soon.

Appendix 1

This agenda and links to many of the talks presented at the Workshop can be found at:

http://www.bnl.gov/rhic/townmeeting/agenda_b.htm

Workshop on pA Physics at RHIC

Saturday, October 28, 2000

Chair: P. Paul

1:30 - 1:35	Introduction, Purpose of the Workshop	S. Aronson
1:35 - 2:15	pA Physics and Relation to AA at RHIC	X. N. Wang
2:15 - 2:45	Color Glass Condensate	R. Venugopalan
2:45 - 3:25	QCD and pA Physics at RHIC	M. Strikman
3:25 - 3:40	Coffee Break	

Chair: L. McLerran

3:40 - 4:10	eA Physics	W. Krasny
4:10 - 4:40	pA Physics and Relation to eA	G. Garvey
4:40 - 5:10	Recent Results from pA	B. Cole
5:10 - 5:40	Results from CDF	A. Bhatti
5:40 - 6:00	Comments on experimental study of the CGC	R. Seto
7:00	Dinner at Senix Creek Inn	

Sunday, October 29, 2000

Chair: R. Tribble

9:00 - 9:30	Polarized pA Physics at RHIC	H. En'yo
9:30 - 10:00	Small-X and Diffractive Production at RHIC	J. Peng
10:00 - 10:30	Gluon Shadowing and Direct γ Production	P. Stankus
10:30 - 10:45	Coffee Break	

Chair: B. Jacak

10:45 - 11:25	Plan for pA Measurements at PHENIX	M. Brooks
11:25 - 12:05	Plan for pA Measurements at STAR	P. Jacobs
12:05 - 1:15	Lunch Break	

Chair: T. Ludlam

1:15 - 1:45	Plan for pA Measurements at BRAHMS	F. Videbaek
1:45 - 2:15	Plan for pA Measurements at PHOBOS	A. Carroll
2:15 - 2:50	pA Accelerator Issues	D. Trbojevic

2:50 - 3:20	Diffractive Production, Luminosity, and Forward Tagging in pA at RHIC	S. White
3:20-3:45	Coffee Break	

Chair: S. Aronson

3:45 - 5:30	Discussions (run plans, detector issues, other physics topics, input to long-range plan etc.	All Participants
	Comments on pA opportunities at RHIC	H. Huang
	Cronin effect via p_T enhancement in pA collisions	G. Fai
5:30	Workshop Adjourned	

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[32] S. White and D. Trbojevic, talk presented at the "Workshop on pA Physics at RHIC," BNL, October 28-29, 2000.

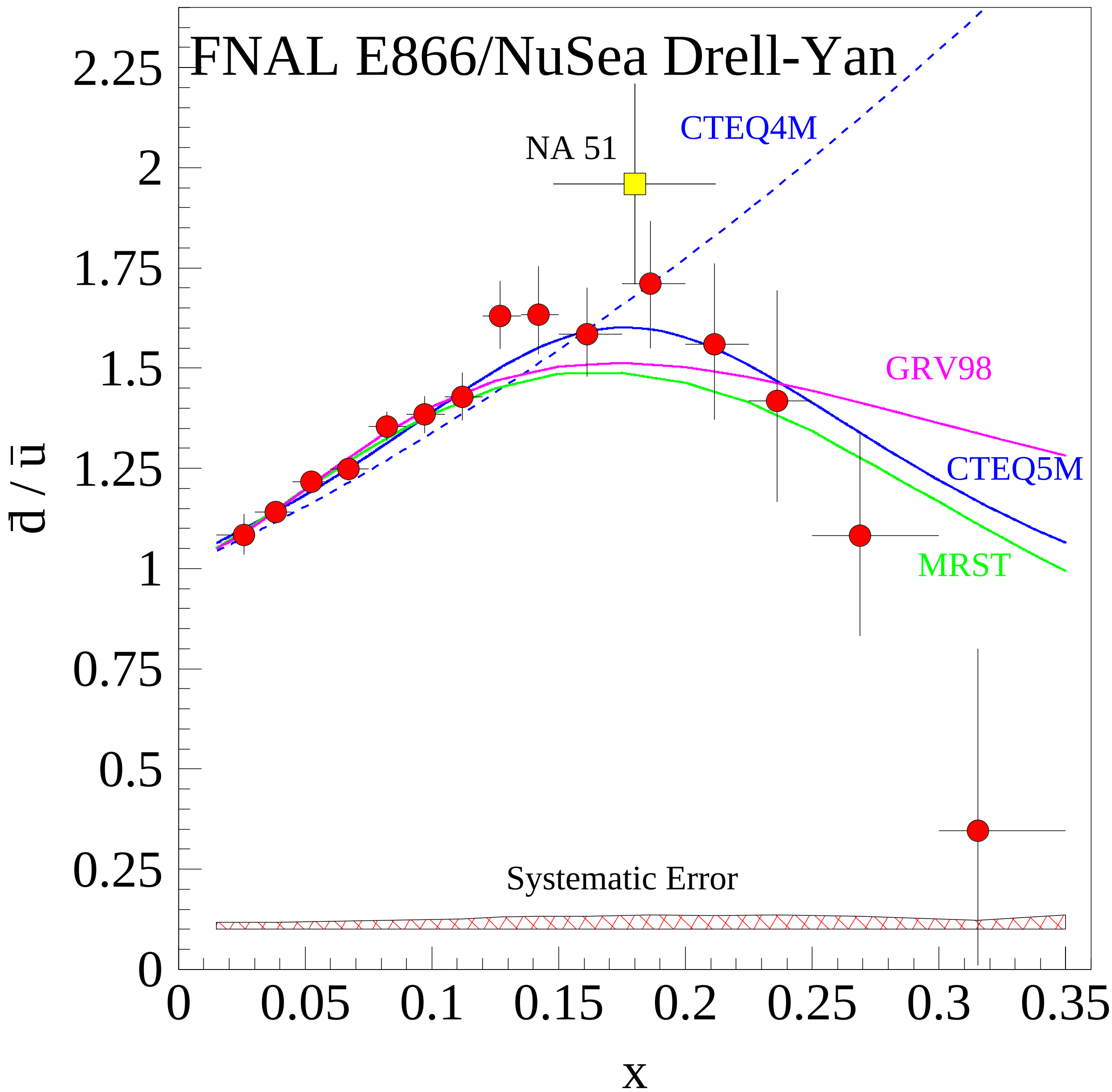
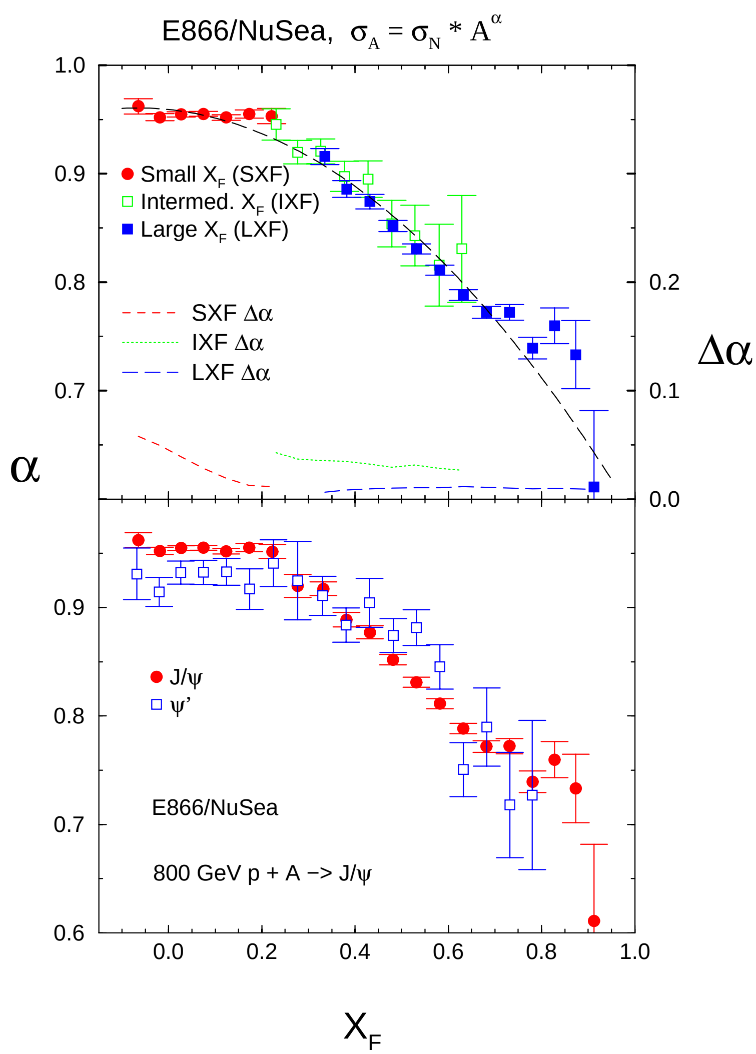


Figure 1: E866 data on $\bar{d}(x)/\bar{u}(x)$ versus x are compared with parametrizations of various parton distribution functions. The data point from NA51 is also shown.



$\alpha(x_F)\ \alpha\ \ 0.96(1-.0519x_F-.338x_F^{\ 2})$

Figure 2: Nuclear dependences for proton-induced J/Ψ and Ψ' production at 800 GeV/c. Data are from Ref. [9]

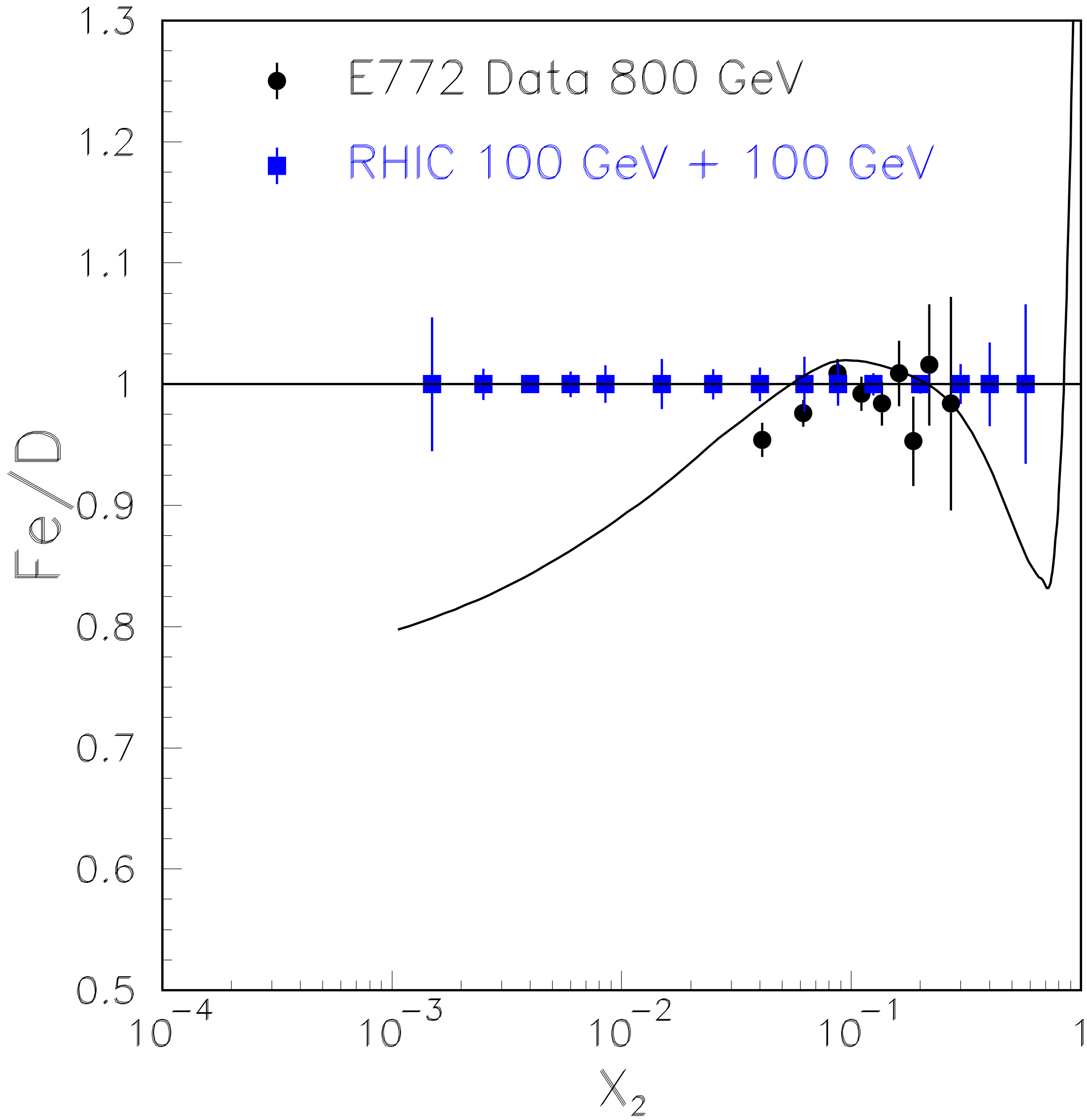


Figure 3: Projected statistical accuracy for Fe/D Drell-Yan cross section ratios as a function of X_2 in a 2-month run at PHENIX. The E772 data are also shown. The solid curve is the EKS98 parametrization for parton distributions in nuclei

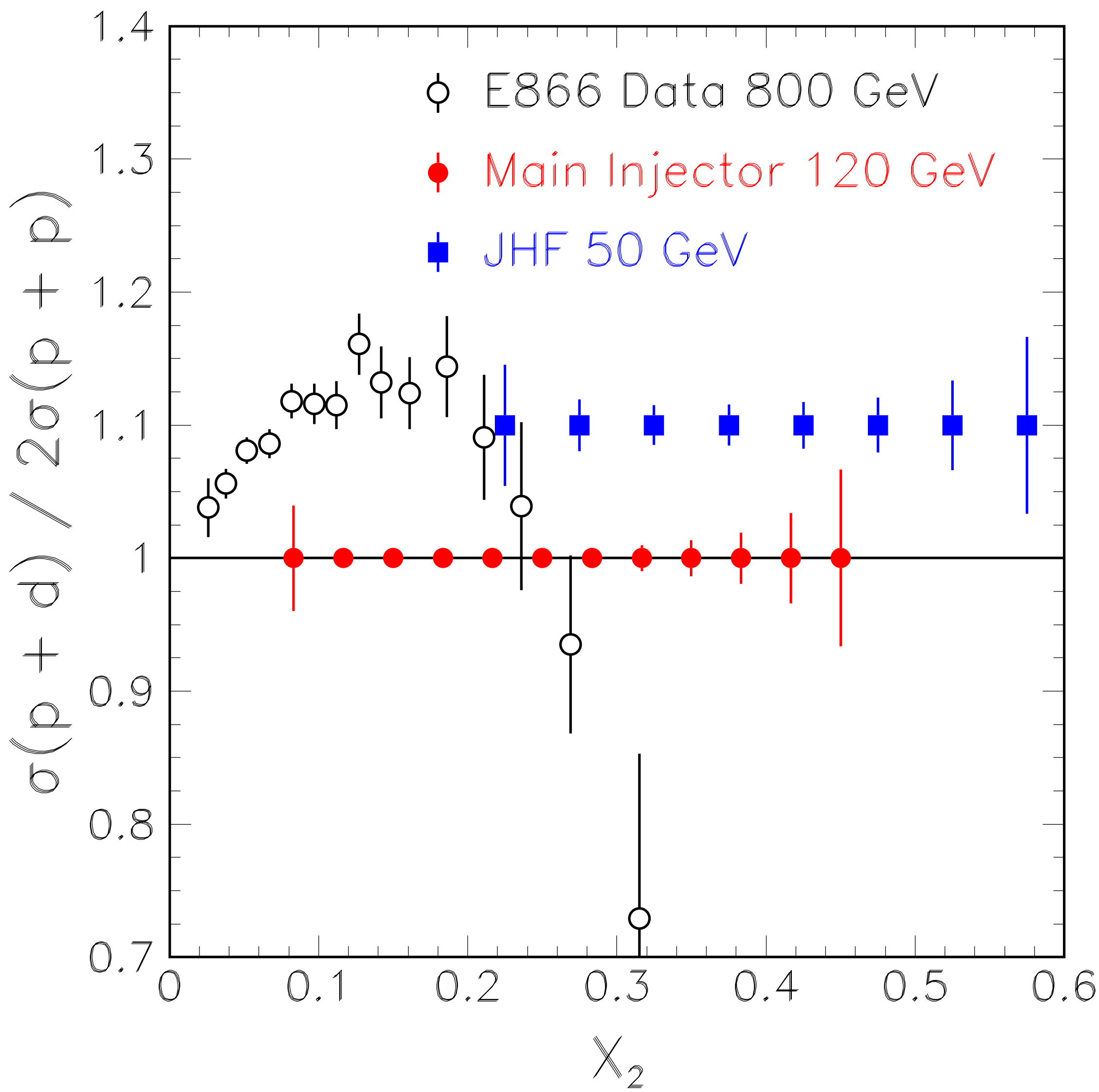


Figure 4: Projected statistical accuracy for $\sigma(p+d)/2\sigma(p+p)$ in a 100-day run at JHF. The E866 data and the projected sensitivity for a proposed measurement [26] at the 120 GeV Fermilab Main-Injector are also shown.

Three possible "p-A" running modes:

1. Symmetric running (100 GeV p + 100 GeV/μ A)

   Advantage:

   - Identical nucleon-nucleon CM energies provide a direct comparison between p-p and A-A.

   Disadvantage:

   - Collision axis will be rotated by up to $\sim$ 4 mr due to the different magnetic rigidities of proton and heavy ion beams. Detector acceptance for p-A is different from p-p and A-A.
   - DX magnets at the interactions region need to be moved.

2. Asymmetric running (250 GeV p + 100 GeV/μ A)

   Advantage:

   - Magnetic rigidities for proton and heavy ion beams are matched. Collision axis will not be rotated. DX magnets will not be moved.
   - Achieve higher CM energies. Reach wider kinematic regions (i.e. small x).

   Disadvantage:

   - Comparison between p-A and A-A is less direct.
   - Feasibility for running the proton and heavy ion beams with different speeds (different orbits in the rings) needs to be demonstrated.

3. d+A running (100 GeV/μ d + 100 GeV/μ A)

   Advantage:

   - Identical nucleon-nucleon CM energies provide a direct comparison between p-p and A-A.
   - Z/A for deuteron is much closer to heavy ions.
   - IR geometry is nearly the same as p-p and A-A.

   Disadvantage:

   - Acceleration of deuterons in RHIC requires work on the ion source and the new RFQ.

Figure 5: Pros and cons of three possible running modes for p-A at RHIC.